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Wavelength-scale Microlasers based on VCSEL-Photonic Crystal Architecture

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WAVELENGTH-SCALE MICROLASERS BASED ON VCSEL-
PHOTONIC CRYSTAL ARCHITECTURE

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27-Sep-2012

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Summary

III-Vs-based microlasers using photonic crystal architecture have been designed, fabricated and tested. The goal was to obtain for the first time a photonic crystal-VCSEL with a total footprint around the wavelength of emission (1550 nm) and operating under electrical injection. We have demonstrated good electroluminescence at room temperature and CW electrical injection. Laser emission by electrical injection has not been yet obtained, probably because the small confinement factor (Q-factor) of the final devices. Nevertheless lasing has been obtained in nanolasers with similar photonic-crystal architecture and bonded to silicon, using optical pumping. Finally, arbitrarily shaped microlasers have been fabricated using photonic crystal architecture.

Introduction

Since the first invention of a laser by Charles Townes in 1950s [1] the laser size has been decreasing steadily. Of particular interests is a semiconductor microlaser, because of its potential uses in optical signal processing within a chip-scale platform. One very well-known, already commercialized example of such microlasers is a vertical-cavity surface-emitting laser (VCSEL).[2] A VCSEL is now indispensable component for various optoelectronic applications, by which fast electrical signals are converted in the form of optical signals. Since the invention of VCSELs, even smaller lasers have been proposed and demonstrated. Examples of these smaller lasers include microdisk lasers [3], photonic crystal lasers[4], and metallic nanocavity lasers[5].

The goal of the present project was to show a new VCSEL-PhC laser, which enables independent control of the degree of the current confinement and the cavity Q. Furthermore, the entire physical dimension of the laser device can be made to fit within a few wavelengths in each spatial direction, which is essential to build a dense array of microlasers within a small footprint. The performance of current VCSELs can be easily overcome by the new PhC laser which should provide large, dense arrays of laser devices with lower threshold, lower power dissipation and lower crosstalk.

Methods, Assumptions, and Procedures

We use an InP/InGaAsP material system emitting at 1.55 μm (grown by molecular beam epitaxy, MBE). We will also assume the triangular lattice of air-holes as a PhC. The entire length of the pillar consists of three major sections – p-InP, i-InGaAsP, and n-InP. Each section is denoted by T_1 , T_2 , and T_3 (thickness of the each layer), which is to be varied to optimize cavity Q and quantum well confinement factor. Laser gain may be provided by quantum wells embedded in the core InGaAsP region. At a wavelength of 1.55 μm , the refractive index of InGaAsP (lattice matched to InP) is about 3.4, while the refractive index of InP is slightly lower than 3.2. Therefore, the refractive index difference between the core and the cladding layer will be larger than 0.2. This index difference is a key to confine an optical mode within the core InGaAsP section (T_2). In traditional VCSELs, multiple periods of alternating high- and low-refractive index layers (called distributed

Bragg reflector, or DBR) are used to achieve the similar mode confinement. However, our new design does not contain such a long period Bragg reflector. We used three $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ quantum wells in the core of an $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}_{0.59}\text{P}_{0.41}$ region ($T_2 = 484$ nm). Top and bottom claddings are InP both of which are 1000 nm-thick ($T_1 = T_3$). The electrical doping structure is of a vertically varying p-i-n, which is equivalent to that of widely adopted in commercialized Fabry-Perot edge emitting lasers. In a conventional edge emitter, an optical mode is confined by the total internal reflection at an interface between the InP cladding ($n = 3.165$) and the InGaAsP core ($n = 3.39$). To utilize this mode confinement mechanism, the Fabry-Perot type laser usually requires a very long cavity length on the order of 0.5-1 mm in order to achieve the lasing threshold condition. However, our new PhC cavity design does not require such a long cavity length; only about one wavelength for all three dimensions, hence a small device footprint of $< 10 \mu\text{m}^2$. Moreover, the actual cavity mode volume (V_{mode}) is in the order of $1.0 (\lambda/n)^3$. The design is not limited to this particular material system and/or the triangular PhC, but can easily modified for various operational wavelengths and/or different crystalline symmetry of the PhC.

Results and Discussion

Several devices were designed using 3D finite difference time domain (FDTD) methods to optimize their optical performance. In principle a relatively high Q factor of $> 2,000$, we can realize a practical form of a semiconductor laser with a quite high Q/V_{mode} . Therefore we can expect many interesting cavity quantum electrodynamics effects such as extremely fast modulation speed [15] and thresholdless lasing behavior [16]. The devices were fabricated on III-V heterojunctions n-type InP/InGaAsP/InP p-type on p-doped InP substrates and were grown by MBE. Electron beam lithography and reactive ion etching was used to deep-etch the holes of the PhC-VCSELS, with around 350nm in diameter and more than $2 \mu\text{m}$ in depth. A top contact made of a thin Au layer was evaporated first to be used as electrical contact and as a mask for the etching procedure. Deep etching using Cl_2 -Ar-CAIBE was used for the dry etching. See Fig.1. Optical characterization was performed using micro-photoluminescence (PL) and electroluminescence (EL) using continuous (CW) excitation. Whereas the devices showed good PL at room temperature, no clear signal of an optical cavity mode was detected. Nevertheless good electroluminescence was detected using a thin wire-W tip placed on the top Au contact (see Fig. 2). V-I curves were obtained for a number of devices, obtaining resistances between 20 Ohm to 1 kOhm. The resistance increased as the area of the device decreased. A schematic electrical model for the device showed that the power $W=IR^2$ scaled as $1/r^6$, in agreement with what it was observed. The micro-needle setup (installed on a vibration-controlled optical table) used for the EL measurement of the V-I curves degraded many of the fabricated devices due to a poor mechanical resistance. A new setup needs to be built in order to finish the EL measurements properly and extract all the performance of the devices. The microdevices may present very interesting properties as microLEDs that could be pulsed at high frequency.

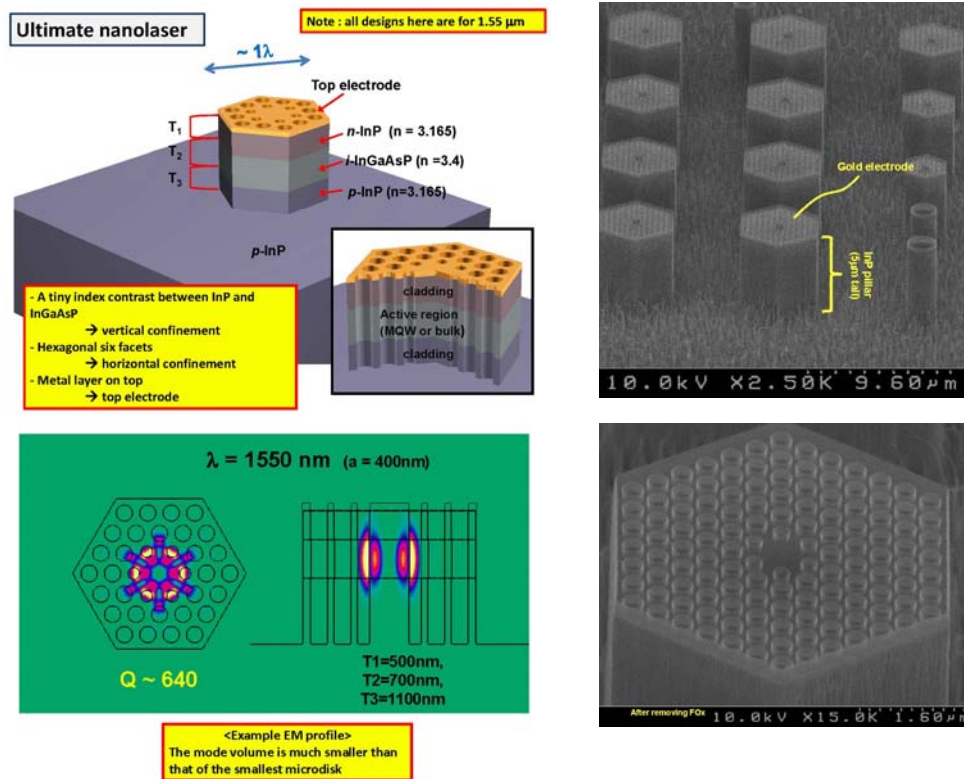


Fig.1. Left panel: design showing that a tiny index contrast between InP and InGaAsP is enough to confine an electromagnetic mode in the vertical direction. In principle, Q is not a sensitive function of T_1 , T_2 , T_3 . T_1 and T_3 can be just about 1 μm to ensure they are long enough in consideration of the evanescent tail of the resonant mode, whereas T_2 can be just over 500 nm. Right panel: SEM pictures of the fabricated devices.

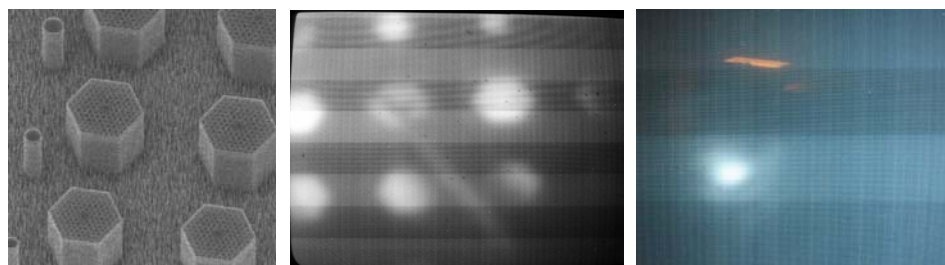


Fig.2. SEM image (Left), CCD image (center) and IR image (right) of one of the microdevices electrically contacted by a micro-needle.

Appart of the resistance, one of the limiting factors for high speed operation is the Q -factor that decreases the maximum switching frequency as the Q increases. In our devices the Q factor may be less than expected, around the hundreds instead that thousands, which may be the reason why the devices did not lase, but, in the other side, may be very useful for switched micoLEDs. Once we test this possibility we can also use a fabrication procedure that can increase the Q -factor and allow

for laser emission, which is the selective etching of the microdevices (see Fig.3) . This method has been used before by the Caltech and IMM groups successfully to enhance the properties of the photonic crystals.

This work has not been published yet although we have obtained two related results that have been published: 1) demonstration of laser emission (using optical pumping) in nanobeam lasers measuring less than 15 μm long and 0.22 μm thick, using InP/InGaAs bonded to a silicon wafer.[6] See attached PPT slide “Nanobeam laser on silicon”. 2) Fabrication and characterization of uniquely and arbitrarily shaped photonic crystal laser cavities were designed.[7] Room temperature lasing emitting around 1550 nm was observed for all devices when photopumped by an 830nm wavelength pulse laser with a pulse width of 100 ns. Continuous-wave lasing was even observed for select devices. See attached PPT slide “Arbitrarily shaped laser resonators”.

Other related results to this grant by IMM’s group are: 1) the demonstration of the first near-thresholdless laser at room temperature by using photonic crystals and InAsSb quantum dots we have obtained a microlaser that shows $\eta=0.85$ and near-thresholdless behaviour at room temperature [8]. See PPT slide “Near-thresholdless lasing at room temperature”. This work will be presented as an invited talk at SPIE San Diego, August 2015. 2) A photonic crystal L7-type cavity light emitter with enlarged free spectral range obtained by selective modal suppression. [9]

Additional selective wet-etching

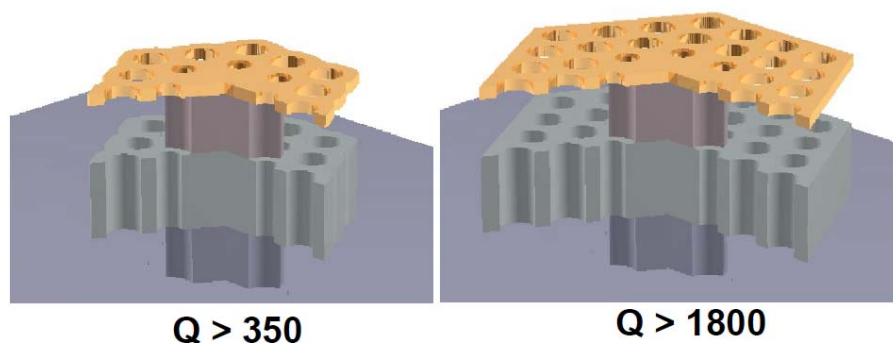


Fig.3. Schematic of the microdevices after selective etching of the InP cladding layers. According to FDTD simulations the Q-factor should increase by a factor of 3.

Conclusions

We have designed, fabricated and tested III-Vs-based light-emitting microdevices using photonic crystal architecture. The goal was to obtain for the first time a photonic crystal-VCSEL with a total footprint around the wavelength of emission (1550 nm) and operating under electrical injection. We have demonstrated good electroluminescence at room temperature and CW electrical injection although laser emission has not been yet obtained. The main reason for the lack of lasing is attributed to the small light confinement factor of the devices (small Q-factor, which is in the 100s). Nevertheless the microdevices may have a very good

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References

- [1] J. P. Gordon, *et al.* "Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3 ", Phys. Rev., Vol. 95, pp.282-284 (1954).
- [2] J. L. Jewell, *et al.* "Vertical-cavity surface-emitting lasers: design, growth, fabrication, characterization," IEEE J. Quantum Electron., Vol. 27, pp.1332-1346 (1991).
- [3] M. Fujita, *et al.* "Continuous wave lasing in GaInAsP microdisk injection laser with threshold current of 40 μA ," Electron. Lett., Vol. 36, pp.790-791 (2000).
- [4] H. G. Park, *et al.* "Electrically driven single-cell photonic crystal laser," Science, Vol. 305, pp.1444-1447 (2004).
- [5] M. T. Hill "Status and prospects for metallic and plasmonic nano-lasers," J. Opt. Soc. Am. B, Vol. 27, B36-B44 (2010).
- [6] 1) "Hybrid single quantum well InP-Si nanobeam lasers for silicon photonics" Fegadolli, W.; Kim, Se-Heon; Postigo, P.A. and Scherer, A.; Opt. Lett., 38 (22) 4656 (2013). In this work we show
- [7] "Uniquely and arbitrarily shaped laser resonators using 2D InAsP/InP photonic crystals" T.-J. Lu, S.-H. Kim, P.A. Postigo, P. Regreny, C. Seassal and A. Scherer. Electronic Lett., 49, 25, pp. 1633-1635 (2013).
- [8] "Near thresholdless laser operation at room temperature" Optica, Vol. 2 Issue 1, pp.66-69 (2015)
- [9] ICTON (<http://www.nit.eu/icton2015>), invited, Budapest, July 2015.

List of Symbols, Abbreviations, and Acronyms

InP: indium phosphide
 InGaAsP: indium gallium arsenide phosphide
 MBE: molecular beam epitaxy
 VCSEL: vertical cavity surface emitting laser
 LED: light emitting diode
 Q-factor: quality factor
 CW: continuous wave
 FDTD: finite difference time domain
 W: power
 I: electrical current
 R: resistance
 PL: photoluminescence
 EL: electroluminescence
 III-V: compound semiconductor
 V_{mode} : optical modal volume
 PhC: photonic crystal
 λ : wavelength
 ns: nanosecond
 nm: nanometer